

FINAL REPORT

Semi-Automated Ferrous Material Scouring System (SAFMSS)

ESTCP Project MR-201102

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Dr. Herman Herman
Mr. Chris Fromme
Carnegie Mellon University

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TABLE OF CONTENTS

TABLE OF CONTENTS	II
LIST OF FIGURES	IV
LIST OF TABLES	V
LIST OF ACRONYMS	VI
1 INTRODUCTION.....	1
1.1 Background	1
1.2 Objective Of The Demonstration	2
2 TECHNOLOGY	3
2.1 Technology Description	3
2.1.1 Drive-by-Wire Excavator	3
2.1.2 Remote Station.....	4
2.1.3 Telemetry and Emergency Override	5
2.1.4 SCARMAG.....	5
2.1.5 Enhanced Teleoperation Capability	6
2.1.6 3D Terrain Mapping Sensor.....	7
2.1.7 Semi-autonomous capability.....	7
2.2 Technology Development	8
2.3 Advantages And Limitations Of The Technology	8
3 PERFORMANCE OBJECTIVES.....	9
3.1 Surface Debris Removal.....	9
3.2 Subsurface Debris Removal	9
3.3 Production	10
3.4 Cost.....	10
4 SITE DESCRIPTION.....	11
4.1 Site Selection	11
4.2 Site History.....	14
4.3 Site Geology	14
4.4 Munitions Contamination.....	14
5 TEST DESIGN.....	15
5.1 Conceptual Experimental Design	15
5.2 Site Preparation	16
5.3 System Specification	16
5.4 Calibration Activities	16
5.5 Data Collection.....	17
5.6 Validation	17
6 DATA ANALYSIS AND PRODUCTS	19

6.1	Preprocessing.....	19
6.1.1	Coverage Rate.....	19
6.1.2	Down Time	22
6.2	Target Selection for Detection	22
6.3	Parameter Estimates	23
6.3.1	Debris Removal	23
6.3.2	Speed, Coverage and Down Time	24
6.4	Classifier and Training	25
6.5	Data Products	25
6.5.1	Initial Test.....	25
6.5.2	Final Test	26
6.5.3	SAFMSS Coverage Map	30
7	PERFORMANCE ASSESSMENT.....	31
7.1	Remove Surface Debris.....	31
7.2	Subsurface Debris.....	31
7.3	Performance.....	31
7.4	Cost.....	31
8	COST ASSESSMENT	32
8.1	Cost Model	32
8.2	Cost Drivers.....	33
8.3	Cost Benefit.....	33
9	IMPLEMENTATION ISSUES	35
10	REFERENCES	36
	APPENDIX A: POINTS OF CONTACT	37

LIST OF FIGURES

Figure 1: Caterpillar 330 excavator	1
Figure 2: Photos of the different parts of the SAFMSS system.....	4
Figure 3: Remote Control Trailer, Controls and Displays	4
Figure 4: SCARMAG	6
Figure 5: SACR Operator Interface colorized by slope	7
Figure 6: Aerial view of the test site – Quantico P-565	11
Figure 7: Range map. Our test was located in the blue region.	12
Figure 8: Aerial view of Range 59 test site at Fort Bliss, Dona Anna Range Complex.....	13
Figure 9: The final field test was performed at the Dona Ana Range Complex on Ft. Bliss.	14
Figure 10: Diagram of sensors and devices used for data collection.....	17
Figure 11: Run 7A based on GPS Location.....	19
Figure 12: Run 7B based on GPS Location	20
Figure 13: Run 7C based on GPS Location Nighttime Run	20
Figure 14: Run 8 based on GPS Location.....	21
Figure 15: The system operated at night.	21
Figure 16: Initial Field Test: Left image of items removed using SAFMSS, right image items removed manually after SAFMSS.	25
Figure 17: Items not removed by SAFMSS, thin walled and dirt filled objects are problematic due to low ferrous material vs weight with soil.	25
Figure 18: Surface debris removed from area near remote control trailer during system training. We used this nearby area to optimize the system for this specific site.	26
Figure 19: Typical of the metal fragments found near a target on the range	27
Figure 20: Final field test items removed by SAFMSS	27
Figure 21: Final field test items removed by SAFMSS	28
Figure 22: Final field test items removed by SAFMSS	28
Figure 23: Final field test items removed by SAFMSS – note all the small metal fragments that were picked up.	29
Figure 24: Aluminum rocket not picked up by SAFMSS. The magnet of SAFMSS cannot pick non-ferrous debris.	29
Figure 25: Dona Anna Range Coverage Map.....	30

LIST OF TABLES

Table 1: Performance Objectives	9
Table 2: Test location and timeline	15
Table 3: Speed and Coverage Calculation Assuming 21 hrs/day (top) and 10 hrs/day (bottom)	22
Table 4: Calculated Down Time	22
Table 5: SAFMSS System Cost Breakdown.....	32
Table 6: SAFMSS Weekly Operation Cost Breakdown	33
Table 7: Cost model for current manual process.....	33
Table 8: Estimated Cost for 200 Acres with Manual Process.....	34
Table 9: Estimated Cost for 200 Acres with SAFMSS, Assuming 21 hrs/day (top) and 10 hrs/day (bottom).....	34

LIST OF ACRONYMS

CAT	Caterpillar Corporation
GPS	Global Positioning System
DGPS	Differential Global Positioning System
GMS	Geophysical Mapping System
GPR	Ground Penetrating Radar
IP	Intellectual Property
MEC	Munitions and Explosives of Concern
MPPEH	Material Potentially Presenting an Explosive Hazard
NREC	National Robotics Engineering Center
SACR	Situation Awareness with Colorized Ranging
SAFMSS	Semi Automated Ferrous Material Scouring System
SCARMAG	SCARifying MAGnet
UXO	Unexploded Ordnance
3D	Three Dimensional

1 INTRODUCTION

The project was focused on developing a Semi-Autonomous System that could be utilized for the remediation of large-scale range clearing projects. The major goals associated with the development of this system are to:

- Increase the speed of range clearing operations
- Improve personnel safety by removing workers from dangerous areas
- Decrease cost to the government by decreasing personnel costs and days to completion.



Figure 1: Caterpillar 330 excavator

1.1 BACKGROUND

Remediation cost on many Munitions and Explosives of Concern (MEC) sites directly relates to the amount of ferrous clutter on the surface and upper band (0-8") of terrain. It is common to remove tons of ferrous scrap for each positive MEC find¹. The surface clutter is laborious to collect while the clutter remaining in the upper soil band results in false positives (digs). Each dig is costly and slows the MEC remediation process. Exacerbating the problem is that ferrous clutter in the upper band of soil may be "locked" in the soil due to vegetation roots and decades of soil compaction. Scrap partially hidden by vegetation or partially buried can be missed by manual methods. While occasional MEC does lay on the surface and in the upper band of soil, at many sites the MEC is 12"-36" deep. It is estimated that MEC remediation cost per acre at many sites could be reduced by 30% or more if surface and near surface ferrous clutter could be efficiently removed before the final mapping and digging process commences. MEC remediation

¹ Comment from Charles Heaton, Shaw Group's Vice President of Shaw's Munitions and Range Sustainment Center of Excellence

project speed would improve by dramatically shortening the most labor and time-intensive process—that of discriminating and digging.

1.2 OBJECTIVE OF THE DEMONSTRATION

Two field tests were performed during the program, the initial field test and shakeout demonstration at Quantico, Virginia and a final field test at Ft. Bliss, Texas.

The first field test was conducted in June 2013 to support NAVFAC Washington at the P565-Remote Parking Lot by performing grid excavations to identify and quantify debris and Material Potentially Presenting an Explosive hazard (MPPEH). AGVIQ CH2M HILL Joint Venture III (JVIII) provided oversight and munitions response services during this demonstration, under their existing contract with NAVFAC Washington.

The Objective of the first field test were:

- Shake out the system and technology by performing real time sustained operations
- Evaluate system performance in real operating conditions.
- Adapt the conceptual operation to conditions encountered to make best use of the technology.
- Work with site managers and UXO technicians to determine appropriate operational methods for planning future deployments.
- Determine system weaknesses (coverage, speed, environmental impact, etc.)
- Collect data to perform initial evaluation of operating cost and performance capabilities/limitations.

The final field test was performed at the Ft Bliss Dona Ana range. The purpose of this test was to get real world data at an active range and to verify the useful application of the SAFMSS system in a large remediation effort. Important data collected during this test included:

- Amount of area covered during total days on site
- Coverage by day
- Efficiency of surface debris removal
- Efficiency of subsurface debris removal
- Peak production efficiency
- Operating and Non-operating time and cause
- Reliability
- Estimated cost to deploy and operate the system

2 TECHNOLOGY

NREC and team member Caterpillar Corporation leveraged existing background intellectual property (IP), hardware and software to economically implement the system. Most of the technology and hardware utilized in this program had been used in other commercial and military programs. In this effort the project team integrated and customized these existing technologies into a Semi-autonomous scouring system, described in the following sections.

2.1 TECHNOLOGY DESCRIPTION

2.1.1 Drive-by-Wire Excavator

Caterpillar retrofitted the control system of a heavy duty excavator (Model 330D) to enable either manual control (with an operator on-board) or control via a remote computer. Sensors, wiring harnesses, electronic control units, and mounting hardware were added to complete the control system (see Figure 2). With very few exceptions, the new control system is created from production parts that have been used for similar configurations on other excavators.

Four high-resolution color cameras housed in environmentally hardened enclosures were mounted on the top of the operator cab to provide the video feedback for teleoperation. Three of these cameras provide the operator a view centered on the excavator boom while the fourth camera looks to the rear. The cameras were mounted to minimize obstruction of the view by the excavator's boom, stick and bucket.

A critical concern for this application is survivability in the event of a rare unintended UXO detonation when the system is operating. As an unmanned application, the SAFMSS operator is located remotely from the work site so the risk of personnel injury or death is decreased. Protection of the equipment is important since SAFMSS includes expensive sensors and computing/telemetry equipment. SAFMSS has an inherent advantage when a detonation occurs since the explosion would most likely take place at the end effector located well in front of the excavator. The end effector would "shield" most of the system from the direct blast as it is essentially a large mass of metal. The end effector may be damaged by the blast depending upon severity but other components are elevated and removed from the blast zone and are likely to survive. Though the excavator hydraulic lines are relatively cheap and easy to acquire and replace, a small amount of armoring is installed to shield these lines. It is impossible to guarantee 100% survivability of the system, but the approach of placing expensive equipment far from the blast as well as removing the operator from the immediate location results in safer operation for both personnel and equipment.



Figure 2: Photos of the different parts of the SAFMSS system

2.1.2 Remote Station

A remote control station was constructed based on ruggedized personal computing technology and flat screen displays (see Figure 3). Images from the excavator mounted cameras are provided on three separate displays arranged to give a forward looking view. Caterpillar used production joysticks and electronic control units for operation of the excavator. NREC and Caterpillar worked together to ergonomically arrange joysticks, foot controls, displays and input devices. All of these components are mounted in a towed trailer for easy transport and protection from the elements.

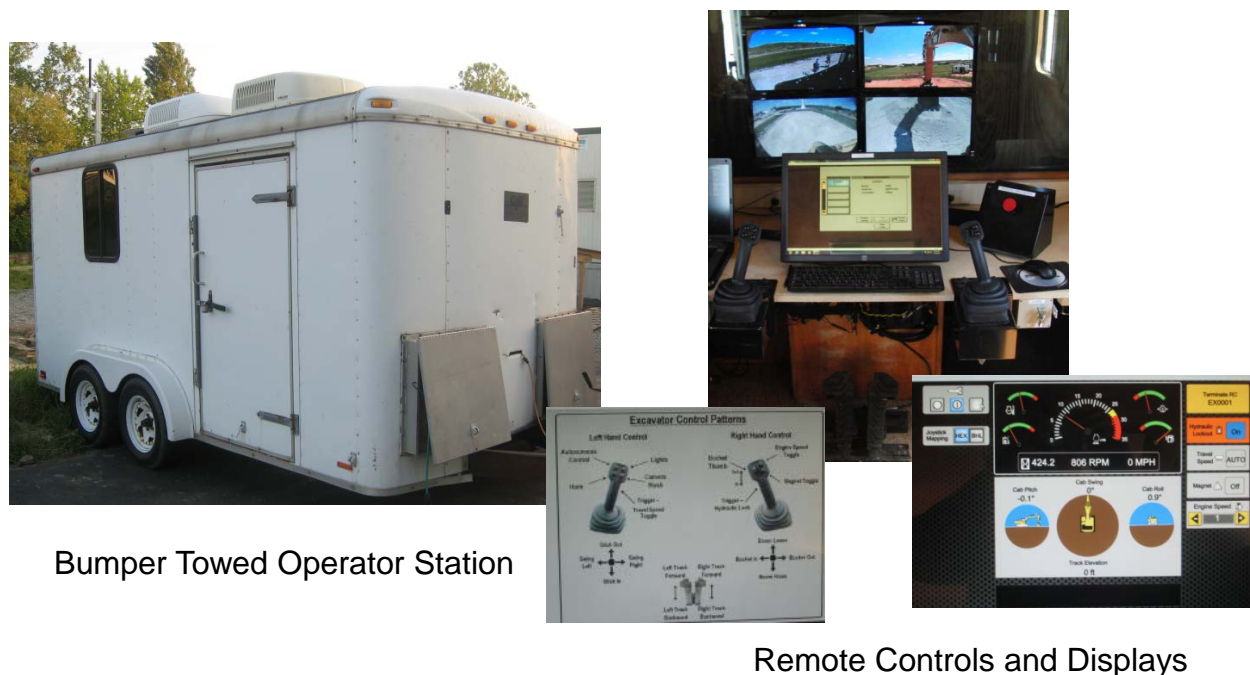


Figure 3: Remote Control Trailer, Controls and Displays

2.1.3 Telemetry and Emergency Override

Telemetry is provided through a wireless link. All data is transmitted, including video, with mild encryption to prevent interference. Video is compressed to minimize bandwidth disturbance. Wireless telemetry does have band width and range limits, but these are not expected to limit SAFMSS operation. A separate E-Stop was also integrated with its own radio link into the system. This approach has been used on most of NREC's systems without a fault to date. Either the operator activates the E-Stop or it is self activated when the radio signal or electronic heartbeat is interrupted.

2.1.4 SCARMAG

The SCARMAG end effector is an integration of a standard excavator bucket, thumb gripper, electromagnet and scarifying teeth. The SCARMAG consists of a bucket, a 16KW electromagnet having an effective diameter of 48", an actuated thumb utilizing the excavator's auxiliary hydraulic circuit for actuation and "teeth" added for scarifying of the soil. The result is a multipurpose tool for the excavator that will improve the way surface and near surface ferrous MEC is removed from ranges (see Figure 4). The SCARMAG can be used in four different operations. The first operation is to remove large brush or obstacles by grappling with the thumb equipped bucket and moving it to the side. The second operation is to sweep across the area to be scoured and push aside smaller brush and obstacles using the integrated "teeth". The third operation is to flip the electromagnet into position and sweep the area to collect surface and near surface (0-8" deep) ferrous debris and deposit in piles or a dumpster like drag box. The last function is to use the scarifying teeth to loosen the soil at an area identified as potentially having significant subsurface clutter and then using the magnet to clear that particular area. An additional capability is to use the system as a traditional excavator to dig and remove large objects, though this capability is degraded slightly by the integration of the magnet into the bucket.

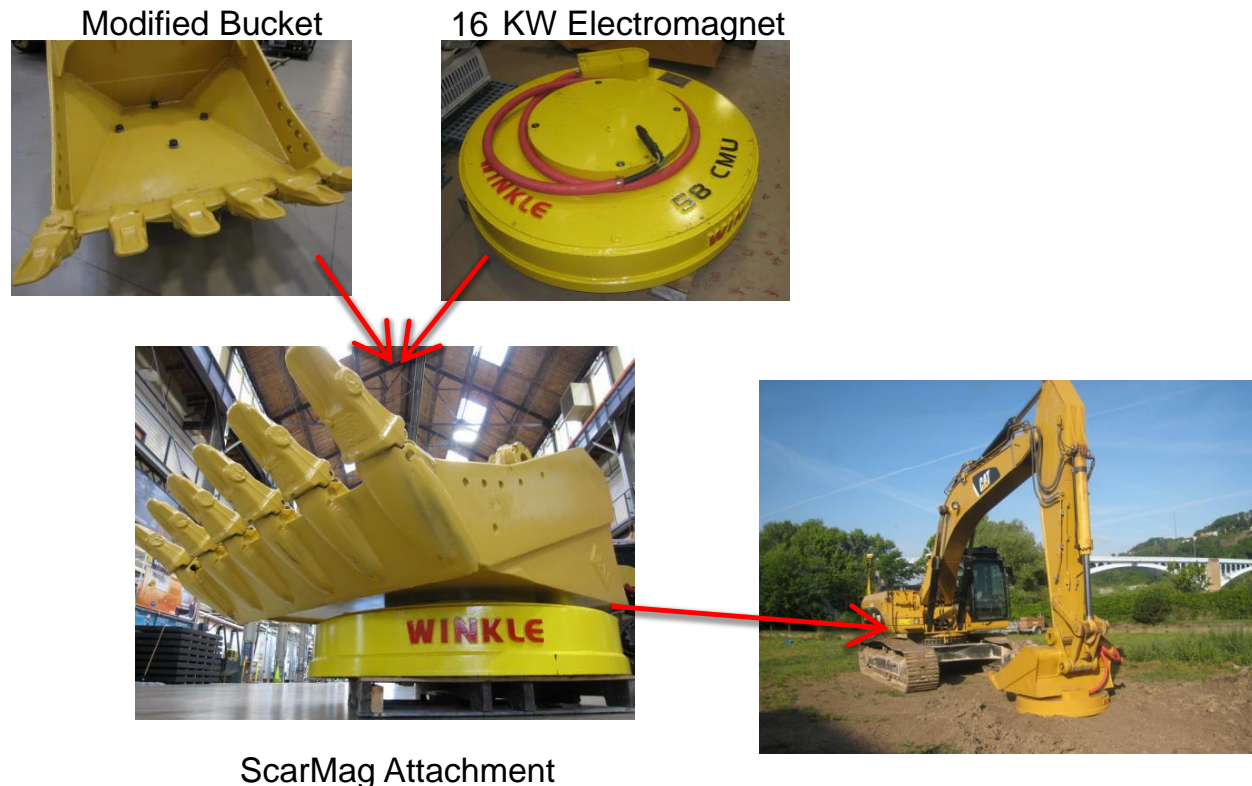


Figure 4: SCARMAG

2.1.5 Enhanced Teleoperation Capability

Teleoperation allows a human operator to remotely control a robot. During operations, the robot must be able to make complex maneuvers and may range far from, and out-of-sight of the operator. Poor situational awareness provided by typical camera-based teleoperation systems makes it nearly impossible for remote operators to match the pace of manned equipment. For teleoperation to work effectively, operators need situational awareness of the system surroundings so that they can plan and act quickly.

NREC has developed an immersive teleoperation system that allows operators to remotely operate an unmanned system more effectively in complex terrain. NREC technology known as SACR (Situation Awareness with Colorized Ranging), generates a synthetic model of the operating environment (see Figure 5). SACR fuses video images and range data in real time to create highly realistic 3D video. Operators can zoom and pan the wide angle 3D view of the excavator's environment. They can shift the virtual camera's viewpoint to different points around the excavator – including a synthetic overhead view – to better see its surroundings. This synthetic view gives remote operators a perpetual synthetic line of sight, a better sense of system surroundings, improves their awareness of the local environment and makes remote and indirect commands safer, easier, and faster.

The SACR software is embedded into the Remote Station (see Figure 3) to create a uniquely capable teleoperation station that makes operators feel as if they're actually sitting in the excavator.

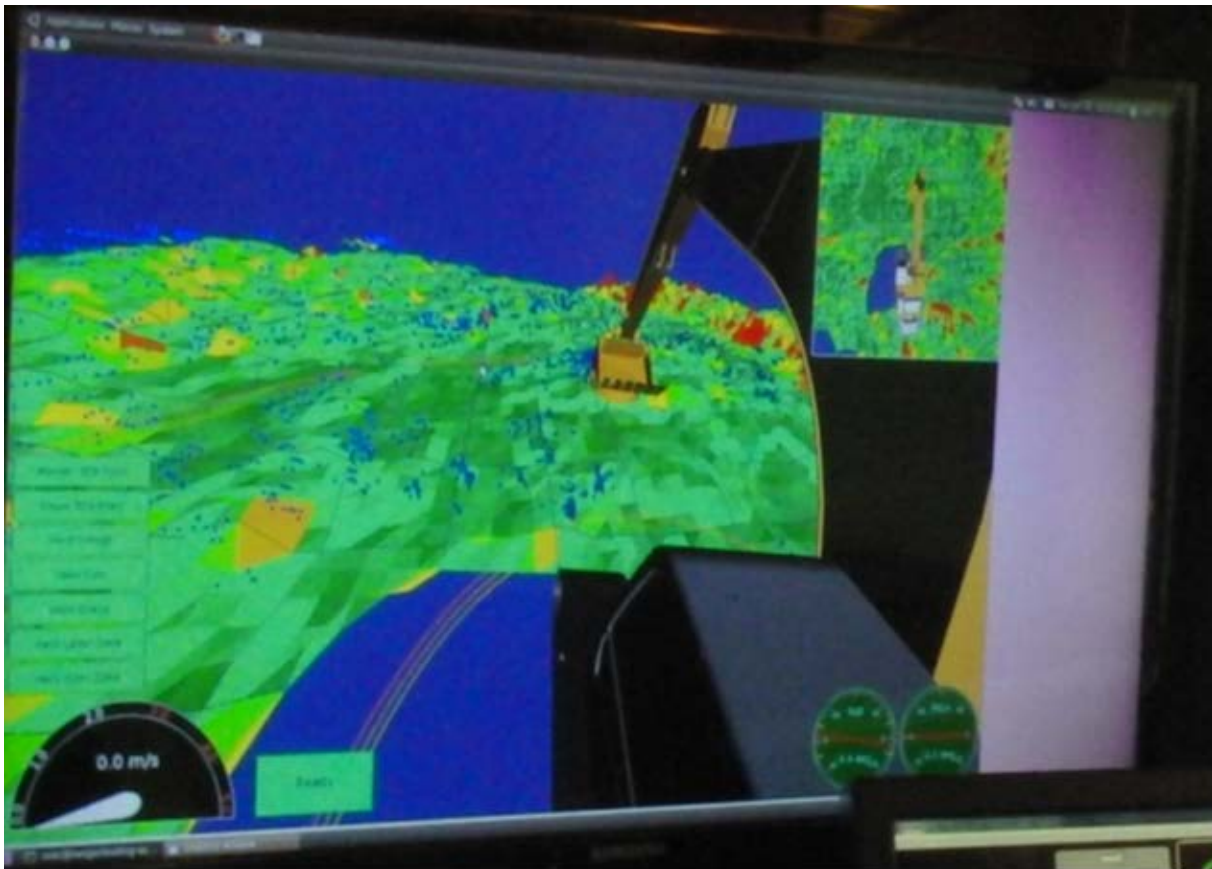


Figure 5: SACR Operator Interface colorized by slope

2.1.6 3D Terrain Mapping Sensor

A laser scanner and vision system are integrated to provide the 3D data for the SACR software. High resolution cameras mounted on the top of the operators cab provides the color video for terrain sensing. A single Sick scanning laser equipped with a “nod” motion is collocated and calibrated with the middle camera to provide the range data used by the SACR software. A ruggedized enclosure protects the scanner from the environment. As the remote operator swings the excavator boom 180 degree, the sensor provides the necessary range and color video data to enable generation of a synthetic operating environment, terrain undulation and obstacle detection.

2.1.7 Semi-autonomous capability

Though the immersive teleoperation capability should dramatically increase operator efficiency over basic remote control, an even greater improvement can be achieved with autonomy aids. NREC implemented capabilities that minimize the efficiency reduction associated with off-the-machine operation and in the case of repetitive tasks, actually increases operator efficiency above in-the-seat capability.

In the specific case utilizing the SAFMSS system, we performed tests comparing manual, remote and semiautonomous operation of the system. The test involved timing a single cycle consisting of sweep, scarify, sweep, moving to the next position. As outline by the bullets below, remote operation covered only 59% as much area as semiautonomous operation. Manual operation only covered 94% of the area that the semiautonomous system could. One must remember that during

the manual and remote tests, the operator was performing at peak efficiency for a short period of time trying to “beat the machine”.

- Manual operation: average time of 6 minutes and 30 seconds per cycle. When including 1 hour for breaks (lunch, etc.) in an 8 hour shift the operator could complete 65 cycles. (
- Remote operation: average time of 10 minutes and 20 seconds per cycle. When including 1 hour for breaks (lunch, etc.) in an 8 hour shift the operator could complete 41 cycles.
- Semiautonomous operation: average time of 7 minutes per cycle. The semiautonomous system can operate for the full 8 hour shift and complete 69 cycles.

Utilizing the terrain map generated with SACR, coverage planning of the designated area is a simple sweep pattern that guarantees overlap and complete coverage while complying with terrain undulations. The operator designates travel speed based on the visible density of surface clutter. Coverage planning takes into account obstacles and operator-identified “keep out” zones to avoid obvious UXOs and other anomalies. The computer generated coverage pattern is overlaid on the synthetic overhead view generated by SACR. The operator can then verify or modify the coverage plan and initiate execution of the sweep. The operator can take over at any time or when the system encounters an unexpected situation. During normal activity, the operator needs to interrupt the operation periodically to dump the load of ferrous material. Once the operator completes a manual operation, he/she hits “resume” and the system completes the plan.

2.2 TECHNOLOGY DEVELOPMENT

NREC and team member Caterpillar Corporation leveraged existing background intellectual property (IP), hardware and software to economically implement the system. Most of the technology and hardware utilized in this program had been used in other commercial and military programs. There is no significant new technology under this project; most of the effort was integrating existing technology and adapting it for this specific application.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Advantages

- Potential night time operation contingent upon regulatory approval.
- Removes people from dangerous areas
- Fast coverage of large areas
- Potentially significant time and cost reductions in reacquisition and manual removal of subsurface anomalies
- System and technology is near production ready with CAT dealer support network.
- Transportable over the road without disassembly (oversize permits required)
- Electromagnet may cause buried ferrous items to exhibit a greater magnetic signature

Limitations

- Cannot pull objects from dense, cohesive soils
- Potential detonation of “live” munitions upon contact with magnet, scarifying teeth or bucket
- May magnetize some soils causing delay in post operation GMS

3 PERFORMANCE OBJECTIVES

As described in Section 5 & 6, both qualitative and quantitative data was collected. The qualitative data was used to estimate the efficacy of the system at removing surface and subsurface debris. The quantitative data was used to calculate the operation rate of the system (i.e. acre per day). Table 1 below shows the main performance objectives as well as the results based on data analysis (see Section 6 for data analysis).

Table 1: Performance Objectives

Performance Objective	Metrics	Data Required	Expected Performance	Results
3.1 Surface debris removal	Qualitative estimate of types and amount of debris removed	Visual observation of:	>90% of loose ferrous debris	~80-90%
3.2 Subsurface debris removal		<ul style="list-style-type: none"> Types of debris removed and missed Estimated amount of debris removed and missed 	> 50% of closed ² ferrous debris within 8 inches	~40-50%
3.3 Production	Acres per day	Log data from system indicating the time that:	>1 acre/day	1.9 acre/day
	Up/down time	<ul style="list-style-type: none"> The magnet is ON The boom is moving The linkage is active The GPS is down 	<20% down time	7.8%
3.4 Cost	Cost per acre	Estimated:	<\$35,000	\$29,978
	Manual vs SAFMSS	<ul style="list-style-type: none"> System cost Operation cost Production rate Manual process cost 	25% cost saving with SAFMSS compared with Manual	29.6%

3.1 SURFACE DEBRIS REMOVAL

The SAFMSS system is very efficient at removing loose debris. Most ferrous debris that is on the surface and mainly composed of ferrous material was picked up. It is estimated that between 80% and 90% of loose debris was removed by the system. As expected, any debris that was not ferrous (e.g. aluminum object) or for which the ferrous content was only a small fraction of its weight (e.g. a ferrous container filled with dirt or other non-ferrous material) was not picked up by our system.

3.2 SUBSURFACE DEBRIS REMOVAL

The ability of SAFMSS to scarify the top 8 inches of the surface loosened up a lot of the debris. This allowed the electro magnet to pick up many ferrous debris but, the system was not successful at picking-up debris that was still stuck in the ground. This was either due to the

² We define close debris as not being able to be filled with dirt, rocks or other material from the environment.

object having some parts deeper than eight inches from the surface or tangled with other features of the terrain (e.g. roots, large rock, etc.). Similar to the surface debris, the system was not able to pick up any non-ferrous debris, or debris for which the ferrous content was only a small fraction of its weight. It is estimated that the system was able to pick up between 40% and 50% of the subsurface ferrous objects not filled with dirt or other non-ferrous material. Because not all debris is in that category, it is estimated that the system was able to pick 1/3 of all subsurface debris. Refer to Section 6 for data analysis.

3.3 PRODUCTION

At the beginning of the project, it was estimated that the system would be able to clear roughly 1 acre per day. However, when assuming 21 hours of operation per day, SAFMSS can clear 1.9 acre per day. Also, GPS data shows that the system was down only 7.8% of the time. All of the down time was caused by loss of DGPS accuracy. We used Differential GPS, which provides much greater position accuracy than single GPS. We determined the cause of the majority of GPS induced downtime was loss of accuracy. Our position threshold was set at 10 cm, when the system exceeded 10 cm accuracy the system would stop until it regained its position within the 10 cm. In hindsight 10 cm was much too tight of a tolerance for this application. If we had doubled the position error to 20 cm, we would have had no downtime because of GPS. We left 8% downtime in our performance calculations to capture other downtime issues that would inevitably occur in a real world deployment.

3.4 COST

The SAFMSS prototype used a Caterpillar 330 excavator. Caterpillar, a subcontractor during the development phase and well aware of the complexity, components and parameters of the system, developed an estimate of \$800,000 for the price of such a system should it build one. This is for building only one system or just a few systems.

Section 8 provides a detailed analysis of the operation cost for SAFMSS. Calculations show that it costs approximately \$29,978 per acre to clear a range with SAFMSS. This is a 29.6% reduction compared with the current manual process.

4 SITE DESCRIPTION

A real range that would provide a large variety of UXO and other anomalies to be extracted was selected for this demonstration.

4.1 SITE SELECTION

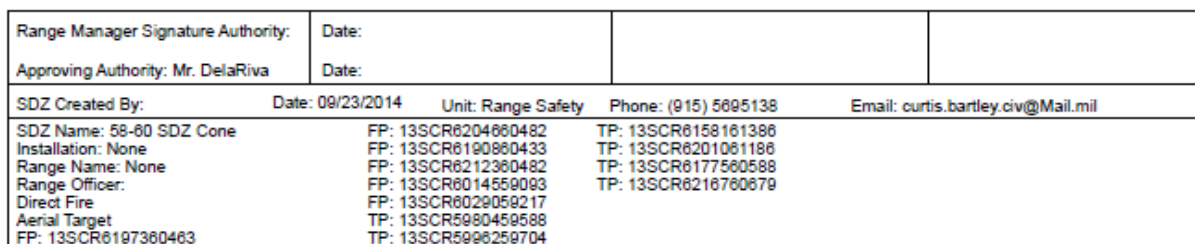
The selected site for the first field test, P-565, was an area on the Quantico Marine Base that is being turned into a parking lot (see Figure 6). During the initial clearing of the area, a bulldozer operator unearthed and unintentionally detonated a smoke grenade. After this event, the site was considered to have Material Potentially Presenting an Explosive hazard and AGVIQ CH2M HILL Joint Venture III (JVIII) was contracted to oversee site assessment and remediation activities.

The site was ideal for an initial shakeout test of the SAFMSS system in a realistic environment. The area is flat, has low vegetation coverage, loam type soil and was expected to have minor MEC contamination but significant subsurface ferrous contamination. The initial GMS was unable to isolate any anomalies because the area is contaminated with multiple unknown ferrous objects.



Figure 6: Aerial view of the test site – Quantico P-565

RMTK Build: 10.1.0.1.3
RMTK Build Date: 10/15/2013



The second field test site was the Dona Ana site at Ft. Bliss, Texas. Ft Bliss was a targeted field test site because there are nearby ranges that are planned to be fully remediated and repurposed

in the near future. The Dona Ana site was selected by access availability assigned by the range manager.

The Dona Anna complex ranges are all active and have been used for many years. It has been used for small arms fire, RPGs, small rockets, mortars, etc. The exact type of munitions is unknown due to its extensive use and little historical documentation. There was a large amount of ferrous debris from various targets used over the years including scraps from 55 gallon barrels, old cars and trucks as well as unidentifiable sources.



Figure 8: Aerial view of Range 59 test site at Fort Bliss, Dona Anna Range Complex.



Figure 9: *The final field test was performed at the Dona Ana Range Complex on Ft. Bliss.*

4.2 SITE HISTORY

The P-565 parking lot was apparently used as either a test range or a general trash site. The exact history is unknown. Based on what the system uncovered the team surmised it was used mostly as a dump site for a mess hall.

The Dona Ana range complex has been used by the army for testing and training for many decades. Once again, the exact overall historical use of the particular range where testing occurred is not fully known due to lack of historical documentation.

4.3 SITE GEOLOGY

The P-565 site was primarily a clayish loam with areas that had been disturbed previously for burial of trash and some old construction materials.

The Dona Ana range complex is primarily an arid sandy soil desert with typical foliage including sage, cactus and other desert plants.

4.4 MUNITIONS CONTAMINATION

The munitions contamination on the P-565 site is unknown. During the initial clearing of the area, a bulldozer operator unearthed and unintentionally detonated a smoke grenade. Once that occurred the area became a munitions response site. During site evaluation, no munitions of concern were uncovered other than a few expended rockets that had been disposed of as trash.

The munitions contamination at the Dona Ana range complex essentially consisted of everything in the current and historical arsenal of the US Army. The full extent of the exact types of munitions are unknown due to lack of historical documentation.

5 TEST DESIGN

The Field Tests performed during this program were performed in real world conditions. It was determined only a real site would provide the ability to fully understand the systems capability. This would not be possible with “seeded” site because it would not be representative of actual conditions and would therefore induce bias in the results.

Testing at the NREC facility was performed prior to the actual field tests. An area was seeded with surface and subsurface ferrous objects and the soil was compacted. The success rate was in excess of 80% item retrieval, but this data is not of any use when determining actual system utility in the real world. The conditions that could not be duplicated during testing at the NREC facility included:

- Compacted soil over many years
- All the various shapes and sizes and density of ferrous material on a real range
- Soil Type
- Vegetation growth (sometimes entangling the ferrous objects in branches and roots)
- Terrain conditions
- Weather conditions, extreme thermal loads from desert sun
- Distance between remote control trailer and SAFMSS (>2000')

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

The design of the experiments was based on performing tests in real world conditions. One challenge was to actually find a site undergoing remediation in the program timeframe and one that would give access to an experimental piece of equipment. It was fortunate to find a site in Quantico for the first field test and then be given permission and a two week window of availability at Dona Anna Range 59. Table 1 shows the different test sites and testing dates.

Table 2: Test location and timeline

June – August 2012	June 2013	December 2014
Seeded test at NREC	Initial Test at Quantico	Final Test at Fort Bliss

The objectives for each field test were:

- Test in a real world environment
- Learn to adapt system for efficient operations
- Collect data logs for performance
- Collect evidence of surface removal efficiency
- Collect evidence of subsurface removal efficiency

Adapting the system to the environment and intended task was the first priority for each field test. NREC worked with the contractors or site managers and UXO technicians to develop a plan of operation and a daily safety plan. During the actual system operation the plan of operation was updated to make the system more efficient.

Collecting data logs, video and visual observation for later analysis was important to enable determination of coverage, speed and efficiency. It was intended that logs of surface and subsurface items both before and after processing the area with SAFMSS using typical metal detectors would be collected. Unfortunately this was not possible. At the Quantico site, the

ground had a magnetic characteristic that prevented the common metal detection sensors from discriminating background noise from munitions of interest. At the Ft. Bliss site it was discovered that the SCARMAG would magnetize the soil, once again rendering the standard magnetic field instruments useless. In addition, NREC learned that supporting UXO technicians were not authorized under a contract to touch objects or disturb soil to assess munition types. While on site, several attempts were made to adjust the sensitivity of the metal detection instruments that would allow detection of subsurface items, but success rate was less than 50% reacquisition, even then there was no way to validate the reacquisition in the field.

The primary data collected for evaluation was video camera. Three cameras were installed, one in the cab looking forward, one near the SAFMSS with an overview and a final camera with a high power zoom located at the remote control trailer.

5.2 SITE PREPARATION

The site preparation involved an initial site visit to scout out the area to determine viable application of the system and educate the site managers and facilitators on the technology that would be tested and support needed.

Once all site personnel agreed to go ahead with the testing any necessary documentation required by the site manager was submitted. After approvals were received the tests were scheduled.

To meet safety protocols, it was arranged either through the site contractor or ESTCP, for two UXO techs to observe operations and serve as site escorts. Once the equipment was on-site the team received safety training and performed a perimeter walk to flag the boundaries, evaluate the terrain and identify any potential trouble spots for the system. Prior to each round of testing, video cameras were placed on and around the system to provide the best views possible.

5.3 SYSTEM SPECIFICATION

See technical description provided in Section 2.

5.4 CALIBRATION ACTIVITIES

The onsite calibrations that were performed were:

- Telemetry range and performance
- GPS calibration/registration
- Linkage sensor calibration
- Professional normal maintenance of the SAFMSS
- Train SAFMSS operation and semiautonomous routines for the terrain/environment

The first calibration performed on site was to make sure the radios were not susceptible to local interference and to determine the maximum range. Antenna location and height was adjusted as needed to maximize range and reduce interference.

The next calibration procedure was to set the parameters of the GPS system for the location of the test. Verification was performed by visually locating the SAFMSS system and Control Trailer on a geo-rectified aerial image.

All position feedback from the SAFMSS linkages was verified and adjusted as needed to ensure autonomous movement was as expected.

A professional CAT technician performed routine inspection and maintenance as needed prior to the start of testing. This included checking and topping fluid levels as needed, lubrication of joints, adjustment of track tension and visual inspections.

The only daily calibration procedure was to modify the manual and semiautonomous routines to maximize system coverage and ferrous material collection. The adjustments were based upon lessons learned from the previous day. For instance the movement speed and height off the ground of the SCARMAG implement was adjusted for optimal surface debris removal. The depth and speed of scarification by the SARMAG teeth was adjusted based on soil type, cohesion and moisture content to achieve the best loosening of the soil without creating large clumps of soil.

5.5 DATA COLLECTION

The experiment focused on collecting qualitative information of the site, the UXO detected and extracted. In addition, the system was equipped with sensors to monitor its progression rate. Figure 10 illustrates the various sensors and devices used for collecting data during testing. The primary quantitative sensors were installed on the excavator itself. These include encoders to measure the linkage motion, base rotation and boom angle. A GPS receiver was also installed to provide accurate location during experiment. All of these devices provided data that was then processed to measure the SAFMSS progress rate (see Section 6.1). The qualitative sensors were a set of cameras installed at different locations. A camera was located near the control station, both located approximately 1,000 feet from the departure point of the excavator. The camera was equipped with a large zoom lens and recorded videos of the operation as the excavator was slowly moving away from the control station. A camera was also installed at the end of the test field to record videos of the system as it is moving toward it. The camera was installed in a location such that the excavator would stop approximately 100 feet away. Finally, a camera was mounted inside the cab of the excavator to record close-up videos of the operation. All of the cameras were mounted in a fixed position and were susceptible to the lighting conditions and other environmental factors.

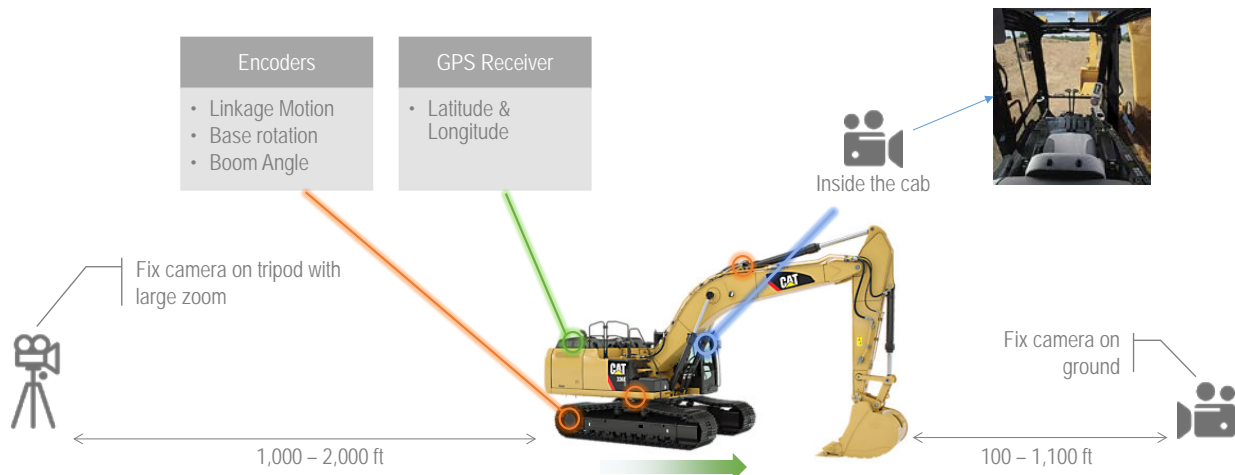


Figure 10: Diagram of sensors and devices used for data collection

5.6 VALIDATION

Due to the fact that the system magnetized the soil, traditional methods (metal detection instrumentation) would not work for validation of removal efficiency. In addition the UXO

techs supporting our effort were not permitted to disturb soil to find any items missed. Because of this quantitative data is not available for analysis.

Speed and coverage is validated by data logs recorded and stored at the remote control station. The primary method of validating the system's ferrous debris removal performance was through review of video footage and walking the area after SAFMSS processing making visual observations. The five team members, including the 2 UXO technicians would visually scour the area for obvious missed items and compared that total with the total removed by SAFMSS.

6 DATA ANALYSIS AND PRODUCTS

As mentioned in previous sections, both qualitative and quantitative data was collected (see Section 5). The qualitative data relates to video footage of the operation during testing as well as photos of debris removed or missed by the SAFMSS system.

6.1 PREPROCESSING

6.1.1 Coverage Rate

Figure 11 is a graph of the typical runtime graph that shows distanced traveled vs time. Using this data from multiple runs, we are able to determine an average coverage rate per hour and uptime/downtime ratio. Table 3 shows the calculations for determining an average coverage in acres per a 21 hour day. Figure 15 shows the SAFMSS system operating at night. We assume 3 shifts of 8 hours each with 1 hour of hand off and maintenance between shifts. In the event that some regulations prevent the use of SAFMSS at night, we also estimated a 10-hour workday that accounts for operation during daylight only. As seen from the Table 3 we averaged 1.94 acres of coverage per day and assuming 21 hours of operation per day and 0.92 cares of coverage per day assuming 10 hours of operation per day. We use this data for calculations in both Sections 3 and 8. Because the system can operation at night (as seen in Figure 15) and the operator is not in proximity of UXO, we believe that 21 hours of operation per day is realistic for future use of SAFMSS and therefore is our baseline for comparing with manual process.



Figure 11: Run 7A based on GPS Location

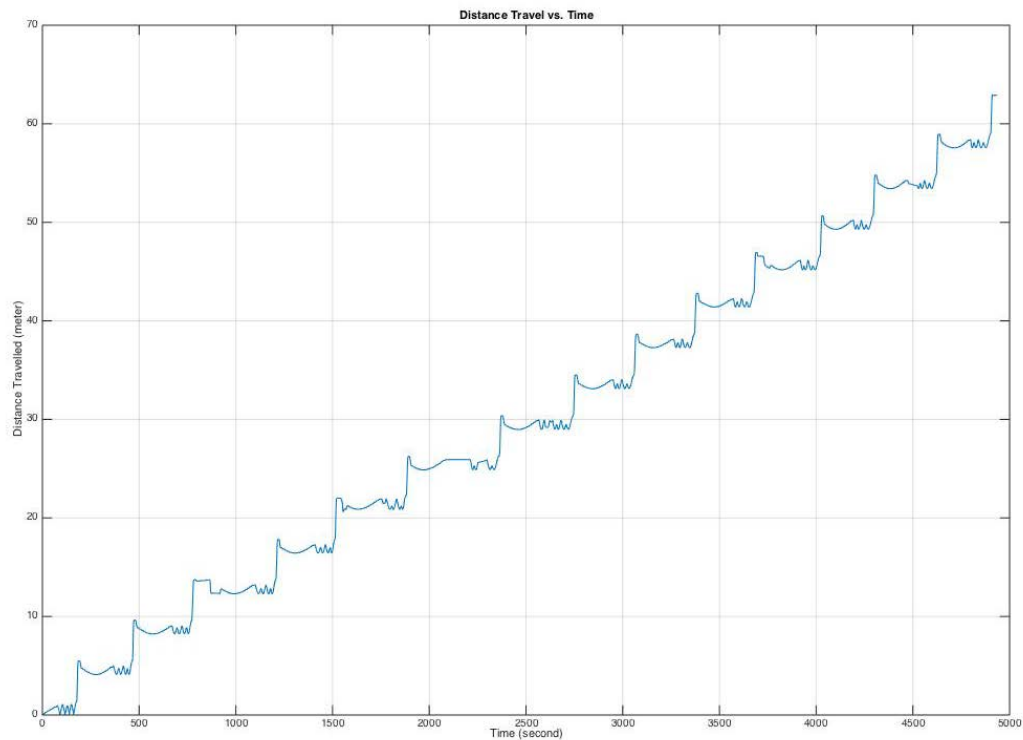


Figure 12: Run 7B based on GPS Location

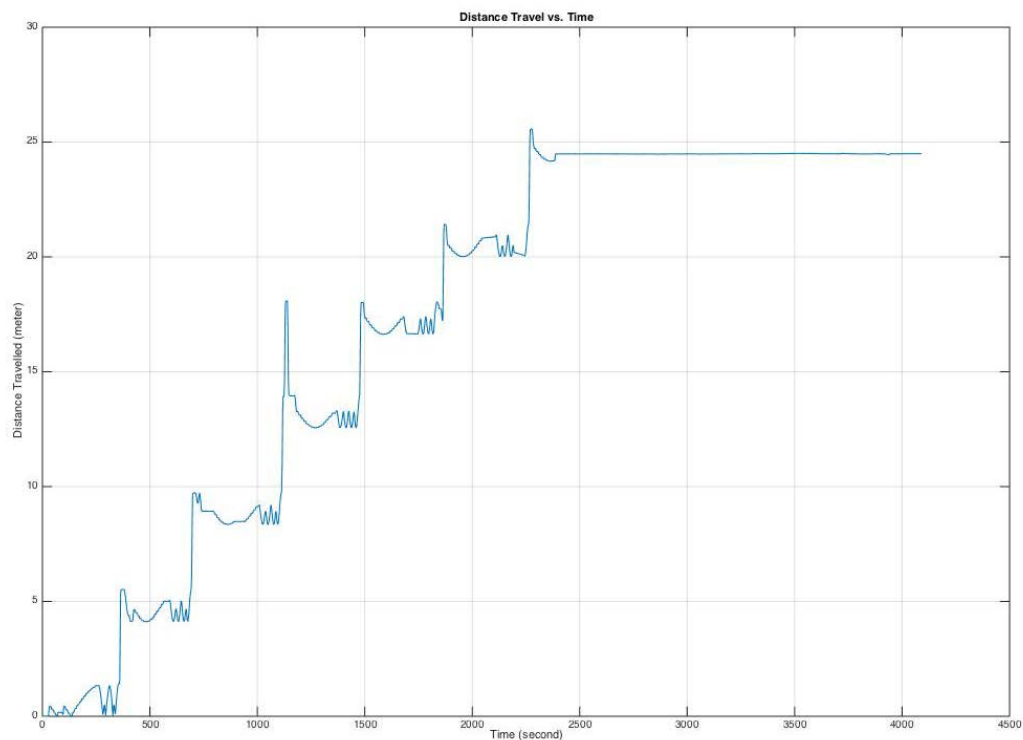


Figure 13: Run 7C based on GPS Location Nighttime Run

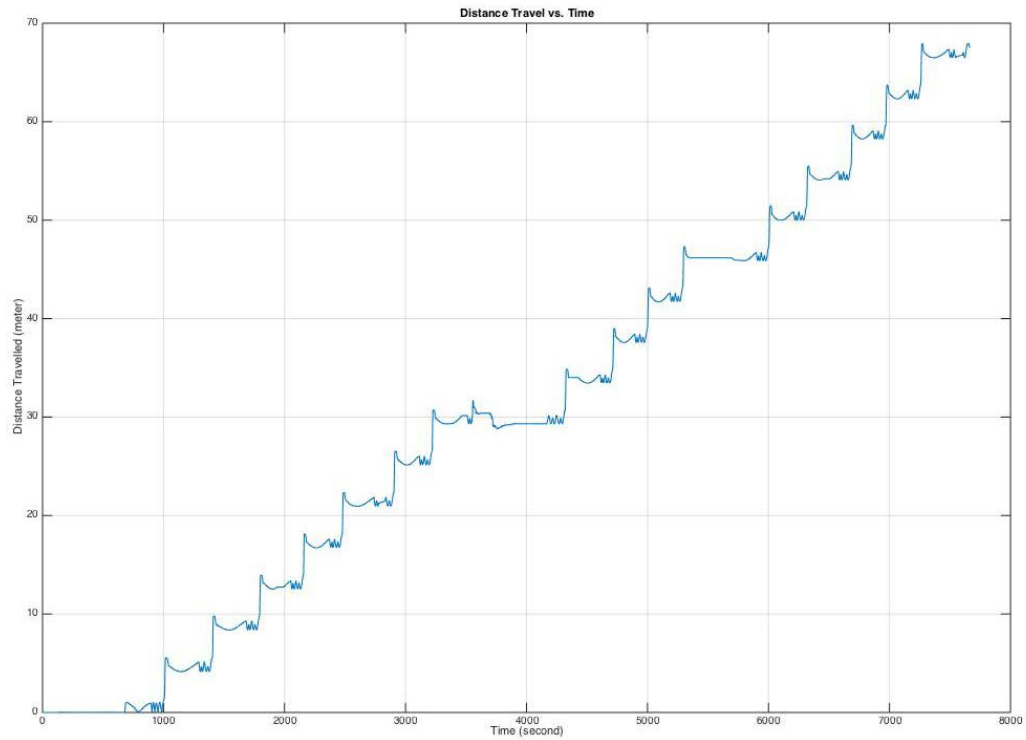


Figure 14: Run 8 based on GPS Location



Figure 15: The system operated at night.

Table 3: Speed and Coverage Calculation Assuming 21 hrs/day (top) and 10 hrs/day (bottom)

Run	Distance (m)	Time (sec)	Speed (m/s)	Speed (m/hr)	Coverage (m ² /hr)	Coverage (acre/day)*
7A	72	8400	0.008571	30.86	329.2	1.71
7B	62	4900	0.012653	45.55	485.9	2.52
7C	24	2300	0.010435	37.57	400.7	2.08
8	68	7600	0.008947	32.21	343.6	1.78
Total	226	23200	0.009741	35.07	374.1	1.94

* Assuming 21 hours of operation per day

Run	Distance (m)	Time (sec)	Speed (m/s)	Speed (m/hr)	Coverage (m ² /hr)	Coverage (acre/day)*
7A	72	8400	0.008571	30.86	329.2	0.81
7B	62	4900	0.012653	45.55	485.9	1.20
7C	24	2300	0.010435	37.57	400.7	0.99
8	68	7600	0.008947	32.21	343.6	0.85
Total	226	23200	0.009741	35.07	374.1	0.92

* Assuming 10 hours of operation per day

6.1.2 Down Time

Using the same data, we calculated down time on each of the figures in Section 6.1.1. Table 4 shows the estimated down time both in seconds and as a percentage of the run time. The average down time during the final test was 7.8%.

Table 4: Calculated Down Time

Run	Time (sec)	Down Time (sec)	Down Time (%)
7A	8400	900	10.7%
7B	4900	300	6.1%
7C	2300	0	0.0%
8	7600	600	7.9%
Total	23200	1800	7.8%

6.2 TARGET SELECTION FOR DETECTION

A real range was selected for this test. The key advantage of using an actual range for this test is to allow the system to operate with real debris in the real environment. However, due to safety reasons, UXO technicians were not able to seed the field before the test nor to excavate any debris or anomalies after the test. Therefore, all of the analysis on the efficacy of the system at removing debris is based on qualitative analysis of video footage.

6.3 PARAMETER ESTIMATES

6.3.1 Debris Removal

In terms of the performance of the system, video footage and photos taken while walking down the field after the system had completed a full pass on a long stretch of the range were reviewed to attempt to determine the amount of surface and subsurface debris removal. Section 6.5 shows the different types of debris that the system easily picked up and the ones that it missed. It is estimated that the system was able to remove from 80% to 90% for the loose ferrous debris. These debris are loose on the ground and are easily picked-up by the magnet. When the debris was completely or partially buried or covered, a drop in system efficacy was observed, as is expected. The scarifying process helped loosen up the ground, but some debris was still stuck in the ground. In some cases, the debris was extending deeper than the 8 inches of the scarifying depth. In other cases, the debris was filled with non-ferrous material. For example, the system was not able to pick up a ferrous container filled up with dirt. The magnet exercises a pull force that is proportional to the mass of the ferromagnetic material, until it reaches its maximum pull force. In the case of a ferrous container filled with dirt (or other non-ferrous material), the pull for the magnet on the limited mass of the container is not sufficient to lift the entire mass of the object. Also, the strong electro-magnet magnetize the ground to a level that affects typical metal detectors. Therefore, buried debris that was not visible could not be detected. The system was not able to pick-up non-ferrous debris (e.g. aluminum shells). With all this in mind, it is estimated that SAFMSS was able to pick up from 40% to 50% of the subsurface ferrous debris that was within 8" of the surface and not filled with dirt (or other non-ferrous material). If the non-ferrous debris or the debris filled with dirt is accounted for, it is estimated that SAFMSS removed 33% of all subsurface debris.

It is very difficult to generate a useful ground truth with this type of development project, however we performed a number of experiments in an attempt to generate a ground truth for the amount of surface and subsurface debris removal. As explained below, we generated our best conservative estimates for use in the cost and performance analysis.

Surface debris removal: We performed two different tests. In the first test at our site (NREC) we seeded the area with a known quantity of ferrous scraps of different shapes, size and weight. We ran the SAFMSS system across the area and every time picked up 100% of the items. This test proved to us that the system worked well but was not representative of an actual site since it did not take into account all possible shapes, sizes and weights of items on a range, nor did it represent real world conditions with various shrubs or grasses entangled with the debris preventing easy removal.

Our second tests were performed at the Dona Anna range in the parking area next to our remote control trailer. We asked the UXO technicians to sweep the area with their metal detectors and mark with paint all the ferrous objects they located on the surface. We then ran the SAFMSS system across the area and recovered more objects than the technicians had located. We performed this test twice with the same results. With these results one could state that we are better at surface debris removal then current manual methods. This would be a false statement since once again these tests were not truly representative of the varying debris field and foliage found throughout the range.

Based on our tests off range and observations on the range (which included counting of visible debris), the five member team came up with our best objective surface removal efficiency of between 80% and 90%.

Subsurface debris removal: To try to determine subsurface debris removal efficiency we performed two sets of tests, one at our site (NREC) and the second in the parking area around our remote control trailer at the Dona Anna range.

Just like in the surface debris removal testing at NREC, we seeded an area with buried ferrous objects of different shapes, sizes and weights. We then ran the excavator across the area in an attempt to compact the soil. We next ran the SAFMSS over the area first scarifying the soil and then sweeping it with the magnet. The first tests actually resulted in recovering more items than were seeded since they were buried there over the decades when the site was used as a foundry. The results from the next set of tests at the same area resulted in debris removal efficiency of between 80% and 100%. This gave us an estimated effectiveness but does not represent the real performance we would expect on a range. Soil types, compaction, shrubs, grasses and roots as well as ferrous content vs item weight all have an effect on actual subsurface removal efficiency.

The second test at Dona Anna was executed in the area near the system remote control trailer adjacent to the range. Soil type and shrubbery were more indicative of the range but not truly representative of the site since type of debris was limited. The UXO techs first did a sweep to remove all the surface debris they could find. Next they performed a sweep and marked all the subsurface ferrous debris they detected. SAFMSS then performed a scarify and magnet sweep of the area. We counted the debris recovered and compared that with the number of locations identified by the UXO techs. Over two tests we recovered over 80% of the ferrous items relative to the number of locations. However this number is of little use since some of the items recovered could have been surface debris that was missed and some of the subsurface locations identified could have been rocks with sufficient ferrous content to set off the metal detectors. We know these rocks exist since we manually recovered them when we were being trained in the detectors operation. No truly useful data came from these tests.

As a team we were unable to generate a tight range for our subsurface removal efficiency since after the system operated over an area the soil became magnetized and the available UXO instrumentation could not detect missed subsurface objects. We decided that 33% was a good conservative efficiency rating for our cost and performance calculations, however we believe the system may actually approach 50% or better which would significantly improve comparable performance and reduce site clean-up costs.

6.3.2 Speed, Coverage and Down Time

The data logs from the GPS receiver were utilized to calculate the total distance covered by the system during a day, the average speed, and the down time.

Distance Covered: During the final two test days, which were the most productive, SAMFSS covered 226 meters in 6.44 hours.

Average Speed: The average speed of SAFMSS is 35 m/hour.

Coverage Rate: SAFMSS performed a sweep that covered a cross track of 10.7 m. Coupled with the average speed above, this produces an average coverage rate of 0.092 acres/hour. The system can operate realistically at about 21 hours per day, which gives a daily rate of 1.94 acres/day.

Down Time: On average, the system was operational 92.2% of the time, giving an average down time of 7.8%. All the occurrences of down time during test were caused by GPS signal loss.

6.4 CLASSIFIER AND TRAINING

SAFMSS does not require a training data set to operate. Prior to the final field test the autonomy system was optimized to follow a specific sweep pattern. The sweep pattern was determined using a representative area near the test site.

6.5 DATA PRODUCTS

Two videos accompany this report. Both videos show SAFMSS during testing. One video was taken during the initial test and the other during the final test.

The sections below include photos showing typical debris encountered during both the initial and final tests.

6.5.1 Initial Test



Figure 16: Initial Field Test: Left image of items removed using SAFMSS, right image items removed manually after SAFMSS.



Figure 17: Items not removed by SAFMSS, thin walled and dirt filled objects are problematic due to low ferrous material vs weight with soil.

6.5.2 Final Test

6.5.2.1 System Optimization



Figure 18: Surface debris removed from area near remote control trailer during system training. We used this nearby area to optimize the system for this specific site.



Figure 19: Typical of the metal fragments found near a target on the range

6.5.2.2 Test Data – Debris Picked-up by SAFMSS



Figure 20: Final field test items removed by SAFMSS



Figure 21: *Final field test items removed by SAFMSS*



Figure 22: *Final field test items removed by SAFMSS*



Figure 23: Final field test items removed by SAFMSS – note all the small metal fragments that were picked up.

6.5.2.3 Test Data – Debris missed by SAFMSS



Figure 24: Aluminum rocket not picked up by SAFMSS. The magnet of SAFMSS cannot pick non-ferrous debris.

6.5.3 SAFMSS Coverage Map

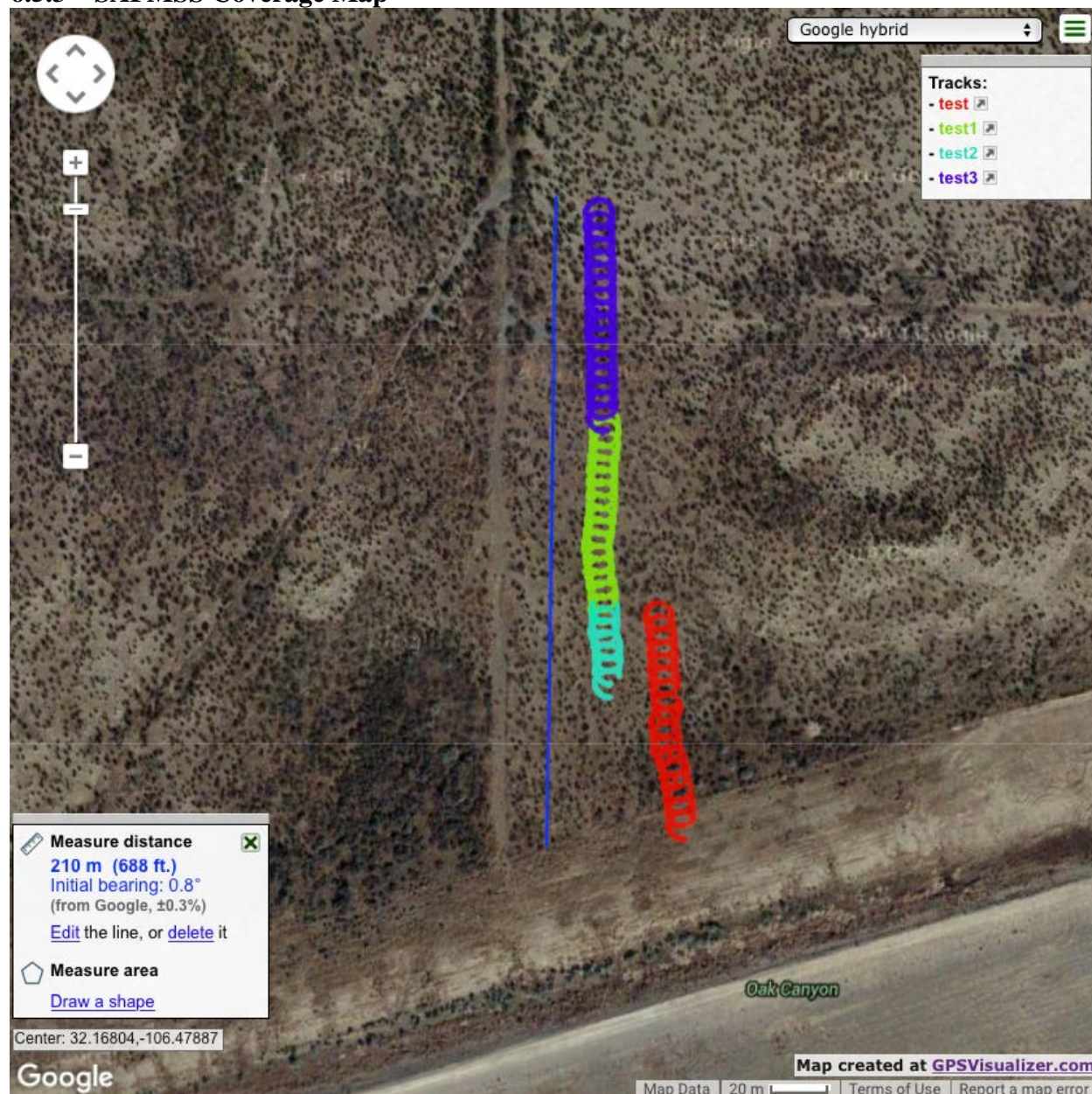


Figure 25: Dona Anna Range Coverage Map

7 PERFORMANCE ASSESSMENT

7.1 REMOVE SURFACE DEBRIS

The performance of the system relating to its efficiency to remove surface debris is addressed and covered in Section 5 & 6. It is estimated that SAFMSS can remove between 80% and 90% of all ferrous surface debris.

7.2 SUBSURFACE DEBRIS

The performance of the system relating to its efficiency to remove subsurface debris is addressed and covered in Section 5 & 6. It is estimated that SAFMSS can remove between 40% and 50% of all ferrous subsurface debris that are not filled with non-ferrous material (e.g. a steel container filled with dirt). The subsurface debris prove to be the most difficult to assess during the final test. The above estimate is based on visual observations of items that were visible but partially buried during the final test, and on system validation using seeded items during on-site testing.

7.3 PERFORMANCE

The average coverage rate of the system along with down time are covered in Section 6. SAFMSS can cover 1.9 acre per day assuming a 21 hour operation with 3 hours for breaks, refueling, shift change, etc. The average down time was less than 7.8%.

7.4 COST

The cost analysis and comparison are covered in Section 8. The estimate shows an average cost of \$29,978 per acre for the operation with SAFMSS. This is 29.6% lower than the current manual process.

8 COST ASSESSMENT

8.1 COST MODEL

SAFMSS

Organizations who need access to large equipment for only specific period of times typically opt for a lease rather than ownership. We assume that range clearing teams who would use SAFMSS in the future would lease the system from a supplier. We asked Caterpillar how much they would charge for a complete SAFMSS system based on their 330 excavator model. They estimated \$800,000 for a complete system. To estimate the weekly rental fee that such a system would require, we compared the weekly rental fee and the purchase price of excavators. Table 5 below lists the purchase price and weekly rental fee for three different excavators from Caterpillar. These numbers were found online from different suppliers and rental centers. The ratio between the weekly rental fee and the purchase price varies from 83 to 143. To be conservative – and to illustrate that the cost savings of SAFMSS are almost insensitive to the system cost or rental fee – we selected the ratio that generates the highest rental fee. With this, we obtained an estimated weekly rental fee for the SAFMSS of \$9,600.

Table 5: SAFMSS System Cost Breakdown

CAT 308E CR	\$100,000
Rental	\$1,200 Weekly
<i>Ratio</i>	<i>83</i>
CAT 329E	\$250,000
Rental	\$7,000 Monthly \$1,750 Weekly
<i>Ratio</i>	<i>143</i>
CAT 316E	\$170,000
Rental	\$2,000 Weekly
<i>Ratio</i>	<i>85</i>
SAFMSS	\$800,000
Rental	\$9,600 Weekly

As shown in Table 6, to estimate the total operation cost per week we added \$1,000 for fuel, \$1,000 for maintenance, and \$9,000 for the operators (including salary with benefits and overhead). This assumes three shifts per day with a total of three operators.

Table 6: SAFMSS Weekly Operation Cost Breakdown

Cost Element	Weekly Lease
SAFMSS	\$9,600
Fuel	\$1,000
Maintenance	\$1,000
Operators (3)	\$9,000
Total:	\$20,600

Manual Process

We estimated the cost of the manual process based upon an analysis performed by the Shaw Group's Charles Heaton, Vice President of Shaw's Munitions and Range Sustainment Center of Excellence. The table below presents Mr. Heaton's cost and productivity estimates for the major tasks of surface material removal, brush clearing, geophysical mapping, anomaly re-acquisition, anomaly excavation and site management. Costs include labor, travel expenses, equipment and supplies and assume a 10 hour work day (see Table 7).

Table 7: Cost model for current manual process.

Function	Weekly Rate	Daily Rate	Production Rate				Units
			Low	Avg	High		
Manual Brush Clearing Team	\$12,115.00	\$3,028.75	1	2	4		Acres/day
5 Person UXO Team - Surface Sweep	\$18,636.00	\$4,659.00	1	2	4		Acres/day
Geophysical Mapping	\$10,000.00	\$2,500.00	1.5	2	2.5		Acres/day
Anomaly Re-Acquisition Team	\$9,895.00	\$2,473.75	100	200	300		Anomalies/day
5 Person UXO Team - Anomaly Excavation	\$18,636.00	\$4,659.00	75	125	150		Anomalies/day
Site Management Team	\$19,842.00	\$4,960.50	1	1	1		Week
SAFMSS Operation (21 hrs/day)	\$20,600.00	\$5,150.00	1.7	1.9	2.5		Acres/day
SAFMSS Operation (10 hrs/day)	\$0.00	\$0.00	1.7	0.9	2.5		Acres/day

8.2 COST DRIVERS

As described in Section 8.3 the cost (or rental fee) of the SAFMSS system is only a small fraction of the total operation cost for a typical site. The main cost savings are related to the system being able to remove a large quantity of anomalies, which are very costly when done with the current manual process. Our recommendations for future improvement are to find ways to improve the efficacy of the system at removing the anomalies and, if possible, accelerate the SAFMSS process to further reduce the number of days required to perform range clearing.

In terms of the current manual process, the cost driver is labor cost. Removing the anomalies is the most labor intensive and is driving most of the operation costs.

8.3 COST BENEFIT

Using the numbers in 8.1, we estimated the total cost and the number of days required to clear a range of 200 acres. Table 8 and Table 9 provide a breakdown of the operation cost for a 200 acre site using the manual and SAMFSS process respectively. For the SAMFSS system, we assumed that it reduced the brush cleaning by 50% and removed 33% of the anomalies.

Table 8: Estimated Cost for 200 Acres with Manual Process

Task	Qty	Units	Prod Rate	Duration (Days)	Daily Rate	Total Cost	Teams Used	Calendar Work Days (adj)	Weeks
Brush Clearing	100 Acres		2	50	\$3,028.75	\$151,437.50	2	25	5
Surface Sweep	200 Acres		2	100	\$4,659.00	\$465,900.00	4	25	5
Geophysical Mapping	200 Acres		2	100	\$2,500.00	\$250,000.00	2	50	10
Anomaly Reacquisition	150,000	Anomalies	200	750	\$2,473.75	\$1,855,312.50	4	188	38
Anomaly Excavation	150,000	Anomalies	125	1200	\$4,659.00	\$5,590,800.00	6	200	40
Site and Project Mgmt	40 weeks				\$4,960.50	\$198,420.00			
						Total: \$8,511,870.00		488	
						Total per Acre: \$42,559.35		2.44	

Table 9: Estimated Cost for 200 Acres with SAFMSS, Assuming 21 hrs/day (top) and 10 hrs/day (bottom)

Task	Reduction	Qty	Units	Prod Rate	Duration (Days)	Daily Rate	Total Cost	Teams Used	Calendar Work Days (adj)	Weeks
Brush Clearing	50%	50 Acres		2	25	\$3,028.75	\$75,718.75	2	13	3
Surface Sweep - SCARMAG		200 Acres		1.9	106	\$5,150.00	\$545,900.00	4	27	6
Geophysical Mapping	0%	200 Acres		2	100	\$2,500.00	\$250,000.00	2	50	10
Anomaly Reacquisition	33%	100,500	Anomalies	200	503	\$2,473.75	\$1,244,296.25	4	126	26
Anomaly Excavation	33%	100,500	Anomalies	125	804	\$4,659.00	\$3,745,836.00	6	134	27
Site and Project Mgmt		27 Weeks				\$4,960.50	\$133,933.50			
						Total: \$5,995,684.50		350		
						Total per Acre: \$29,978.42		1.75		
						Reduction -29.6%		-28.3%		

Task	Reduction	Qty	Units	Prod Rate	Duration (Days)	Daily Rate	Total Cost	Teams Used	Calendar Work Days (adj)	Weeks
Brush Clearing	50%	50 Acres		2	25	\$3,028.75	\$75,718.75	2	13	3
Surface Sweep - SCARMAG		200 Acres		0.9	223	\$5,150.00	\$1,148,450.00	4	56	12
Geophysical Mapping	0%	200 Acres		2	100	\$2,500.00	\$250,000.00	2	50	10
Anomaly Reacquisition	33%	100,500	Anomalies	200	503	\$2,473.75	\$1,244,296.25	4	126	26
Anomaly Excavation	33%	100,500	Anomalies	125	804	\$4,659.00	\$3,745,836.00	6	134	27
Site and Project Mgmt		27 Weeks				\$4,960.50	\$133,933.50			
						Total: \$6,598,234.50		379		
						Total per Acre: \$32,991.17		1.895		
						Reduction -22.5%		-22.3%		

The operation cost breakdown for the SAFMSS system Table 9 above clearly shows that the main cost driver is the labor cost associated with detecting and excavating the anomalies. The cost of the SAFMSS system or its lease fee is not a significant driver. Because the SAFMSS is able to remove 33% of the anomalies, the overall operation cost is therefore reduced to \$29,978 per acre (assuming 21 hours of operation per day as the baseline), a 29.6% reduction compared with the process that relies entirely on manual labor. In addition, the SAFMSS system reduces the time required to clear a range by 28.3%.

9 IMPLEMENTATION ISSUES

During the project, a few issues were discovered that would need to be corrected to enhance the performance of the system and enable operational deployment.

- 1 Magnetization of the soil makes traditional instrumentation based on magnetic field detection unusable. Alternative instrumentation such as GPR or other non-magnetic based instrumentation must be used in conjunction with a SAFMSS system to complete a remediation program. It was not determined if the magnetization of the soil decays over time or not.
- 2 Training of operators and maintainers is needed to keep costs in line with the savings projections. It only takes 1 person to operate the system, but typically there would be 2 (the buddy system). Both operating and maintaining the system requires specialized training.
- 3 Since SAFMSS is a hydraulic powered system, spills during remote operation could become a major issue without some sort of spill sensing. To our knowledge there is no automated system provided by OEM excavator manufacturers to detect fluid leakage remotely.
- 4 The SAFMSS had scarifying teeth that were 18" long. Scarifying teeth 24" long would be significantly more effective at breaking up soil to the desired 8 to 12 inches depth.
- 5 An independent pan-tilt-zoom high-resolution camera for the system operator to remotely identify areas/objects of concern/interest would be needed in the final implementation. Every UXO technician and observer of the system in observation made this comment.
- 6 A more refined cost model is needed to evaluate if this type of system could reach the critical mass needed to become economically viable. Performance and operating cost calculations show significant savings over traditional methods, however items like training of operators and maintenance personnel, higher pay rates due to higher education requirements, any additional certifications, additional regulations and requirements that may be imposed on the deployment of the system and additional reporting are not taken into consideration.
- 7 All technologies and sensors are available off-the-shelf but this was the first custom implementation and integration of all these technologies for this application. Hardening and commercialization of the independent components would be the next step.
- 8 The ROM cost estimate to build SAFMSS from CAT in a quantity of one is roughly \$800,000. A critical mass needs to be reached to drive the operating cost to the point it becomes more affordable. In other words, a single system needs to be nearly fully utilized for an 8 to 10 year period to make ownership and cost savings realizable.

10 REFERENCES

None

APPENDIX A: POINTS OF CONTACT

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
Daniel Stanek	Caterpillar Inc Peoria, IL	309-213-0232 STANEK_DANIEL@cat.com	Caterpillar Integration
Chris Fromme	NREC Carnegie Mellon University 10 40 th Street Pittsburgh PA 15201	412-559-9766 ccf@rec.ri.cmu.edu	Principle Investigator
Dr. Herman Herman	NREC Carnegie Mellon University 10 40 th Street Pittsburgh PA 15201	412-576-9020 herman@nrec.ri.cmu.edu	Principle Investigator
Ed Robbs	Range Developer Ft Bliss Training Center	915-569-9743 carl.e.robbs.civ@mail.mil	Ft Bliss Site Facilitator
Fred Evans	Remedial Project Manager CIV NAVFAC Washington	202-685-3303 frederick.j.evans@navy.mil	Quantico site Facilitator
Stephen J. Matney	AGVIQ, LLC 4610 Westgrove Court Virginia Beach, VA 23455	757-213-8583 smatney@tikigaq.com	Quantico Site project Manager